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Active Versus Passive Cooling During Work in Warm Environments While Wearing Firefighting Protective Clothing

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This study examined whether active or passive cooling during intermittent work reduced the heat strain associated with wearing firefighting protective clothing (FPC) and self-contained breathing apparatus (SCBA) in the heat (35° C, 50% relative humidity). Fifteen male Toronto firefighters participated in the heat-stress trials. Subjects walked at 4.5 km·h^{-1} with 0% elevation on an intermittent work (50 min) and rest (30 min) schedule. Work continued until rectal temperature (T_{re}) reached 39.5° C, or heart rate (HR) reached 95% of maximum or exhaustion. One of three cooling strategies, forearm submersion (FS), mister (M), and passive cooling (PC) were employed during the rest phases. Tolerance time (TT) and total work time (WT) (min) were significantly increased during FS (178.7 ± 13.0 and 124.7 ± 7.94, respectively) and M (139.1 ± 8.28 and 95.1 ± 4.96, respectively), compared with PC (108.0 ± 3.59 and 78.0 ± 3.59). Furthermore, TT and WT were significantly greater in FS compared with M. Rates of T_{re} increase, HR and $\dot{T}_{sk}$ were significantly lower during active compared with passive cooling. In addition, HR and T_{re} values in FS were significantly lower compared with M after the first rest phase. During the first rest phase, T_{re} dropped significantly during FS (~0.4° C) compared with M (~0.08° C) while PC increased (~0.2° C). By the end of the second rest period T_{re} was 0.9° C lower in FS compared with M. The current findings suggest that there is a definite advantage when utilizing forearm submersion compared with other methods of active or passive cooling while wearing FPC and SCBA in the heat.

Keywords cooling strategies, exercise tolerance, metabolic rate, protective clothing, rectal temperature, uncompensable heat stress

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Firefighter protective clothing (FPC) offers an increased protection from both hazardous materials and extreme environmental heat for short periods of time. However, although FPC is necessary for firefighter safety, it is not without its shortcomings. The current firefighting protective ensemble is heavy, thick, multilayered, and bulky; and it exacerbates the challenge of thermoregulation due to limited water vapor permeability, increased metabolic load, and insulative properties.[1,2] Unable to maintain thermal equilibrium, the firefighters continue to store heat, elevating core temperatures and creating a competition between their cardiovascular and thermoregulatory systems for cardiac output. If a firefighter remains in this environment, his or her core temperature will continue to rise to dangerous levels, leading to potential heat exhaustion, disorientation, syncope, myocardial infarction, or even death.[3–6]

In light of the inherent trade-off between personal protection and the well-documented cardiovascular and thermoregulatory strain associated with firefighting activities,[7–11] there is a requirement to develop methods for keeping firefighters' cardiovascular and thermoregulatory strain below critical levels during work in FPC. Work and rest schedules can be implemented to extend operations beyond those performed in a continuous fashion.[12] However, it has been found that with hot and/or humid conditions, rectal temperature (T_{re}) will not decrease during passive rest, and, in fact, will continue to increase during the designated rest periods due to the environmental conditions.[7,9,13,14] Thus, when ambient temperatures are high, the implementation of work and rest schedules will extend exposure time but not the total amount of work accomplished. If body cooling can occur during periods of rest, then implementing work and rest schedules can increase the total work time while reducing heat strain.[15] It has been postulated that in such instances, active cooling can be incorporated into the standard work and rest schedules to promote a negative heat balance.[16]

Various methods for cooling have been reported, including precooling,[17,18] liquid and air cooling systems,[16,19,20] water immersion of the extremities, both hands[20–22] and feet,[23] as well as fan cooling.[24] Liquid and air cooling systems offering continuous[16] and intermittent[19] microclimate cooling

have been found to deliver sufficient cooling power to effectively reduce heat strain during moderate to heavy work. Depending on the working conditions, these methods have the potential to change an uncompensable working environment to compensable.[19,25] Another approach is to adapt the technology of these devices into portable units. However, current portable cooling devices generally use complicated equipment, are expensive and cumbersome, and add to the already elevated metabolic demand for a given activity.[19,25,26] In addition, practicality and mobility could be limited with tethered systems or portable units where extended periods of exposure to harsh or dangerous environments are necessary. An alternative cooling method to personal mounted devices is extremity immersion.[20,22,23,26] A comparison between an ice-vest configuration and hand immersion found that the small advantage acquired through constant cooling during work when using an ice vest was surpassed by hand immersion in 20°C water during scheduled rest periods.[20]

Fan cooling has been found to attenuate the increase in rectal temperatures during work and rest schedules; however, as rectal temperature approached 38.0°C, it continued to rise during subsequent recovery periods.[24] Therefore, it remains to be seen how effective active fan cooling would be following additional bouts of work as firefighters approach critical limits. Portable misters using the concept of flash evaporation have the potential to reduce elevated local ambient environmental conditions. It is possible that additional cooling potential supplied by a fan and mist combination might have the potential to further decrease the rate of rectal temperature increase observed with fan cooling alone.[24]

Given the reported benefits of limb submersion and fan/mister cooling, these modalities were selected as the two most practical and cost-effective cooling methods to be examined. Thus, the purpose of the present study was to compare active and passive cooling strategies during intermittent rest periods and to determine whether one modality was more effective than another in aiding heat transfer from the body while wearing FPC.

METHODS

Subjects

Following approval by the Defence Research and Development Canada (DRDC)—Toronto's Human Ethics Review Committee, 15 subjects were selected from a pool of 40 active Toronto firefighters to participate in the cooling trials described below.

Baseline testing was completed in August and the trials were conducted in the climatic chamber at DRDC Toronto between September and January to limit heat acclimation through casual exposure to hot environments. All subjects were medically screened and a full explanation of procedures, discomforts, and risks were given prior to obtaining written informed consent. Subjects were selected so the age, aerobic fitness, and body fatness covered a wide spectrum of individuals who were representative of the Toronto Fire Service.

Determination of $\dot{V}O_{2peak}$

Peak oxygen consumption ($\dot{V}O_{2peak}$) was measured at a comfortable room temperature (22°C) by open-circuit spirometry on a motorized treadmill using an incremental protocol.[27,28] $\dot{V}O_{2peak}$ was defined as the highest observed 30-sec value for oxygen consumption ($\dot{V}O_2$) together with a respiratory exchange ratio ≥ 1.15. Heart rate (HR) was monitored during the treadmill protocol using a transmitter/telemetry unit (Polar Vantage XL, Kempele, Finland). The highest value recorded at the end of the exercise test was defined as peak HR (HR_{peak}).

Body surface area was calculated using the DuBois equation.[29] Body density was determined from underwater weighing using body plethysmography to determine residual lung volume.[30,31] Body fatness was calculated using the Siri equation.[32]

Clothing Ensembles

During work, subjects wore their own National Fire Protection Association standard protective firefighting turnout gear (Garment Model-BPR5442TK, Morning Pride, Dayton, Ohio), gloves (Shelby Firewall, Memphis, Tenn.), Nomex® flash hood (Majestic Fire Apparel, Lehighton, Pa.), helmet (Firedome PX Series, Bullard, Ky.), and self-contained breathing apparatus (SCBA) (MSA, Pittsburgh, Pa.). Standard issue cotton station pants and a Toronto fire T-shirt were worn beneath the turnout gear, along with underwear, shorts, socks, and running shoes. The Canadian Forces' nuclear biological and chemical (NBC) impermeable protective overboot was worn in place of the standard rubber boot to simulate the impermeable characteristics of the rubber boot. The total weight of the ensemble approximated 22 kg. During all trials, subjects breathed room air as opposed to SCBA; however, full SCBA was carried to simulate the weight of the bottle. The total thermal resistance of the FPC ensemble, determined with a heated articulating copper manikin, at a wind speed of 0.85 $m \cdot s^{-1}$, was 0.240 $m^2 \cdot °C \cdot W^{-1}$ (1.55 clo). The Woodcock vapor permeability coefficient, determined with a completely wetted manikin, was 0.27.[33]

Experimental Design

All subjects performed a familiarization exposure (35°C, 50% relative humidity (RH), wind speed <0.1 $m \cdot s^{-1}$), at the designated work rate (4.5 $km \cdot h^{-1}$, 0% incline) until attaining one or more of the specific end-point criteria (see below). The familiarization trial was at least 10 days before their first experimental trial to limit the acute effects of acclimation. Each subject then performed randomly assigned experimental sessions at 35°C and 50% RH, while wearing FPC and SCBA. The protocol time line was broken into work and rest phases as shown in Figure 1.

Work Phase

Each work cycle was divided into a work portion and a simulated SCBA bottle change, which have been previously

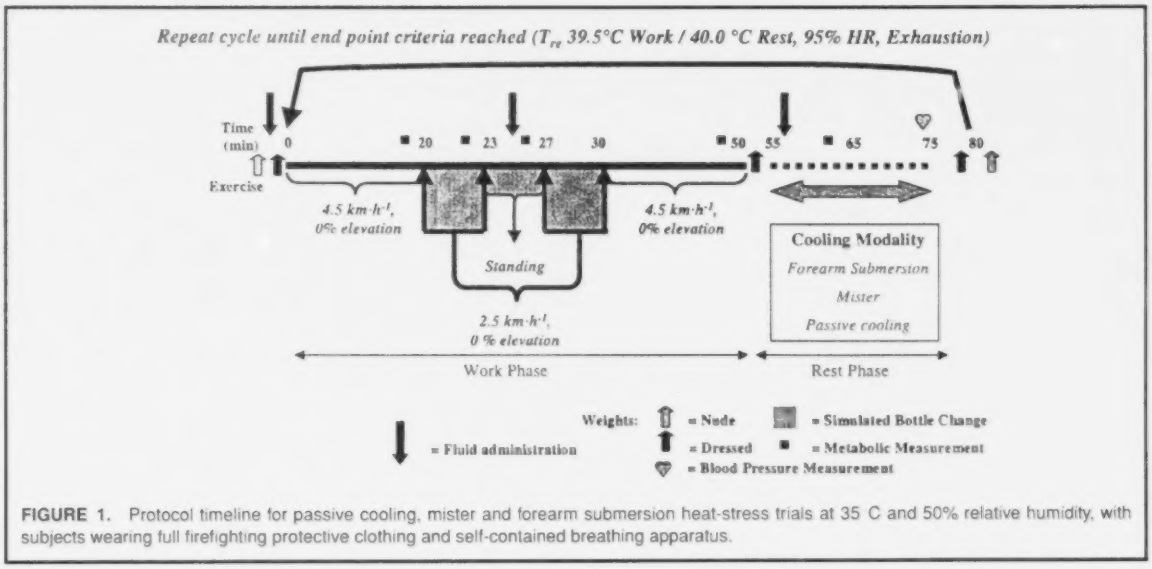

FIGURE 1. Protocol timeline for passive cooling, mister and forearm submersion heat-stress trials at 35 C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus.

described in detail.[13] The work portion consisted of walking at 4.5 km·h^{-1} for 20 min while wearing the protective ensemble and SCBA. Following 20 min of work, a 10 min simulated SCBA bottle change occurred (see Figure 1). A portion of our "work" period involved 6 min of lighter work and a 4-min period of standing rest to simulate a cylinder change compared with the other 20-min exercise period. Nevertheless, we have chosen to maintain this terminology of "work" and "rest" periods since the cooling cycles involved an entire period of seated rest. Following the 10 min simulated bottle change subjects began another 20-min work portion.

Rest Phase

Following the second 20-min work portion, a 30-min rest phase began at 50 min. The first 5 min of the rest phase was allotted for disconnecting the data acquisition system; obtaining a dressed weight; and removing helmet, flash hood, gloves, jacket, tanks, and SCBA facepiece. At min 55, subjects received one of three 20-min cooling strategies. Following either active or passive cooling, a second 5-min transition period allowed subjects to reencapsulate, obtain a dressed weight, and reconnect to the data acquisition system before beginning another work phase starting at 80 min. The intermittent work and rest phases (50/30 min) were repeated until one or more of the following end-point criteria were reached: T_{re} reaching 39.5°C, HR reaching or exceeding 95% of maximum for 3 min, dizziness or nausea precluding further work, subject exhaustion or discomfort, completing 4 cycles of work (290 min), or the investigator terminating the trial. End-point criteria for the rest phase were similar to the work phase except that the T_{re} ceiling was raised to 40°C. If T_{re} had not decreased below 39.5°C by the end of a rest phase, subsequent work was not performed. Tolerance time (TT) was defined for all trials as the elapsed time from the beginning of the work to the attainment of one or more of the end-point criteria that resulted in the termination of the trial. Total work time (WT) was defined as TT minus the time spent during rest.

Cooling Strategies

Passive Cooling (PC)

Following transition between phases, subjects remained seated in the climatic chamber for 20 min. Although bunker pants were not taken off, the subjects were allowed to undo the Velcro® closure on the front of the pants.

Forearm Submersion (FS) (active)

Forearm submersion was accomplished using an insulated calorimetry tank (16.2 cm H × 27.5 cm W × 82.5 cm L) placed at one end of the climatic chamber. The tank was temperature controlled (17.4 ± 0.2°C) prior to submersion to simulate a typical summer hose-line water temperature. During submersion, subjects leaned over the tank with hands and arms submerged to the elbow joint for 20 min. During submersion, the tank was manually stirred and water temperature was recorded every 5 min. The amount of heat (Q in watts) transferred from the hands and forearms to the calorimeter was determined using the following equation:[23]

$$Q = (mc \cdot t^{-1})(T_i - T_f - \Delta T_c) \quad (1)$$

where m is the mass of water (3.6×10^4 g), c is the specific heat of water (4.2 J·g^{-1}·°C^{-1}), t is time (1.2×10^3 s), T_i is the water temperature when hands and forearm were submerged (°C), T_f is the water temperature when the hands and forearms were removed, and ΔT_c is the change in calorimeter water temperature due to environmental conditions when hands and forearms were not submerged.

Mister (M) (active)

A Versa Mist™ cooling system (Thermal Dyn, LLC, Sauk Rapids, Minn.) was used for the mister cooling trials which delivered fan propelled fine mist vapor at a rate of 2000 cubic feet per min. Subjects were seated approximately 5 ft in front of the mister in the climatic chamber for 20 min. The wind speed at the point of contact for the subjects was 1.94 $m \cdot s^{-1}$ (7 $km \cdot h^{-1}$). Local ambient temperatures and humidities were recorded at the beginning and every 5 min during the mister cooling phase.

Dressing and Weighing Procedures

To control for the effects of circadian rhythm on rectal temperature, all trials began at 7:30 a.m.[34] On arrival, subjects inserted a rectal probe and were weighed nude on an electronic scale, sensitive to the nearest 0.05 kg (Serta Systems Inc., SuperCount, Acton, Mass.). Skin thermistors and HR monitor were applied, and then subjects were dressed in station pants and T-shirt, followed by bunker pants, jacket, flash hood, running shoes, and an NBC overboot. Following water administration, subjects donned SCBA tanks respirator facepiece, flash hood, helmet and gloves to obtain full encapsulation. Subjects were then led into the climatic chamber where a final dressed weight was obtained, and skin and rectal thermistor monitoring cables were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer, and 2934A printer, Pittsburgh, Pa.). Subjects straddled the treadmill walking surface and a treadmill speed of 4.5 $km \cdot h^{-1}$ with 0% elevation was established before beginning the first work phase.

On completion of each work and rest phase, and on completion of the trial, a dressed weight was obtained encompassing all gear. The subjects were removed from the climatic chamber and nude weight was recorded within 5 min of trial termination, after subjects undressed and towelled dry.

Fluid Replacement and Sweat Measurements

During the familiarization exposure, subjects were given 5 $mL \cdot kg^{-1}$ of cool water (~15°C) to drink, prior to entering the climatic chamber, at min 25 of each 30-min work/SCBA bottle change cycle and at the beginning of each rest phase. If T_{re} exceeded 39.0°C or if the subject felt that he or she could not continue for at least another 10 min, water was not administered for the remainder of the intermittent heat-stress trial. Sweat rate (SR) was calculated from the familiarization trial and this value was used to determine rates of fluid replacement that would maintain a state of euhydration during subsequent experimental trials. For all trials, nude and dressed masses were corrected for respiratory[35] and metabolic mass losses,[36] as well as for fluid intake. The rate of sweat production (SR) incorporated the entire heat-stress trial.

Physiological Measurements

Temperature Measurements

Mean values over 1-min periods for T_{re}, and a 7-point weighted mean skin temperature ($\bar{T}_{sk}$)[37] were calculated, recorded, and printed by the computerized data-acquisition system. T_{re} was measured using a flexible vinyl-covered rectal thermistor (YSI Precisions 4400 Series, Yellow Springs Instrument Co. Inc., Yellow Springs, Ohio), inserted approximately 15 cm beyond the anal sphincter. $\bar{T}_{sk}$ was obtained from seven temperature thermistors (Mallinckrodt, Medical Inc., St. Louis, Mo.) taped on the head, abdomen, medial deltoid, hand, anterior thigh, shin, and foot. Mean body temperature ($\bar{T}_b$) and changes in body heat storage (ΔS, in kJ) were calculated using the following equations:[22]

$$\bar{T}_b = 0.33\bar{T}_{sk} + 0.67T_{re} \quad \textbf{(2)}$$

and

$$\Delta S = mc\bar{T}_b \quad \textbf{(3)}$$

where m is the mass of the subject (kg) and c is the specific heat of the human body (3.48 $kJ \cdot kg^{-1} \cdot °C^{-1}$).

Heart Rate and Blood Pressure Measurements

Heart rate was monitored using a transmitter (Polar Vantage XL) attached with an elasticized belt fitted around the chest and taped in place. The receiver was taped to the outside of the clothing, allowing for a continuous HR display. HR was recorded manually every 5 min during both the work and recovery phases of the heat-stress trial. Blood pressure was taken prior to blood sampling and at the end of each rest phase for the heat-stress trials using a standard stethoscope and pressure cuff technique.

Mean arterial pressure (MAP) was approximated using the equation:

$$MAP \approx P_{Diastolic} + \frac{1}{3}(P_{Systolic} - P_{Diastolic}) \quad \textbf{(4)}$$

where P represents pressure.

Gas-Exchange Measurements

Details of the open-circuit spirometry used to determine expired min ventilation, $\dot{V}O_2$, and carbon dioxide production have been presented previously.[28] Measurements were made during min 17–20, 20–23, and 47–50 of each 50-min work, plus simulated bottle change cycle and during min 12–15 of each rest phase. Values were averaged from a 2-min sampling period for each subject following a 1-min washout period. The current SCBA facepiece outtake valve was modified to incorporate the attachment of an adaptor that allowed expired gases to be collected during work.

Blood Sampling and Measurements

A 5-mL blood sample was obtained by venipuncture prior to the dressing procedures to determine osmolality using the Advanced™ Micro-Osmometer (Model 3300, Advanced Instruments, Norwood, Mass.).

Rating of Thermal Comfort

A subjective rating of thermal comfort (RTC) was completed immediately following metabolic gas exchange measurements using a modified version of Gagge et al.[38] The

RTC scale ranged from 7 ("comfortable") to 13 ("so hot I am sick and nauseated").

Statistical Analyses

A one-factor (cooling strategy) repeated measures analysis of variance (ANOVA) was used to compare the dependent measures of osmolality, fluid consumption, mass loss, TT, WT, and SR. An ANOVA with two repeated factors (cooling strategy and time of exposure) was performed on the various dependent measures sampled over time (i.e., ΔT_{re}, $\bar{T}_{sk}$, $\bar{T}_b$, RTC, $\dot{V}O_2$, Q, ΔS, and HR) for the heat-stress trials. To correct for violations in the assumption of sphericity with the repeated factors, the Huynh-Feldt correction was applied to the F-ratio.[39] When a significant F-ratio was obtained, post hoc analyses used a Newman-Keuls procedure to isolate differences among the treatment means. All ANOVAs were performed using statistical software.[40] For all statistical analyses, an alpha level of 0.05 was used.

RESULTS

Subjects

Subject anthropometric characteristics for age, height, mass, surface area, and body fatness were 40.7 ± 0.82 years, 181.1 ± 1.8 cm, 86.9 ± 2.1 kg, 2.07 ± 0.03 m^2, and 17.5% ± 0.9%, respectively. $\dot{V}O_{2peak}$ and HR_{peak} were 45.7 ± 1.4 mL·kg^{-1}·min^{-1} and 190 ± 2.4 b·min^{-1}, respectively.

Osmolality

There were no significant differences in preosmolality values across the three cooling trials with mean values approximating 288 mOsm·kgH_2O^{-1}, a value that is within the accepted range for a normal hydrated state.[41]

Gas Exchange

There were no significant differences in $\dot{V}O_2$ observed throughout the heat-stress trials. After 20 min of work, $\dot{V}O_2$ averaged 12.1 ± 0.2 mL·kg^{-1}·min^{-1} and represented a workload of approximately 30% $\dot{V}O_{2peak}$.

Blood Pressure

There were no significant differences observed between trials or overtime for systolic, diastolic, or MAP. MAP ranged between 83 and 100 mmHg throughout the trials.

Heart Rate

Figure 2 presents the HR response over time for the heat-stress trials. As expected, there were no significant differences

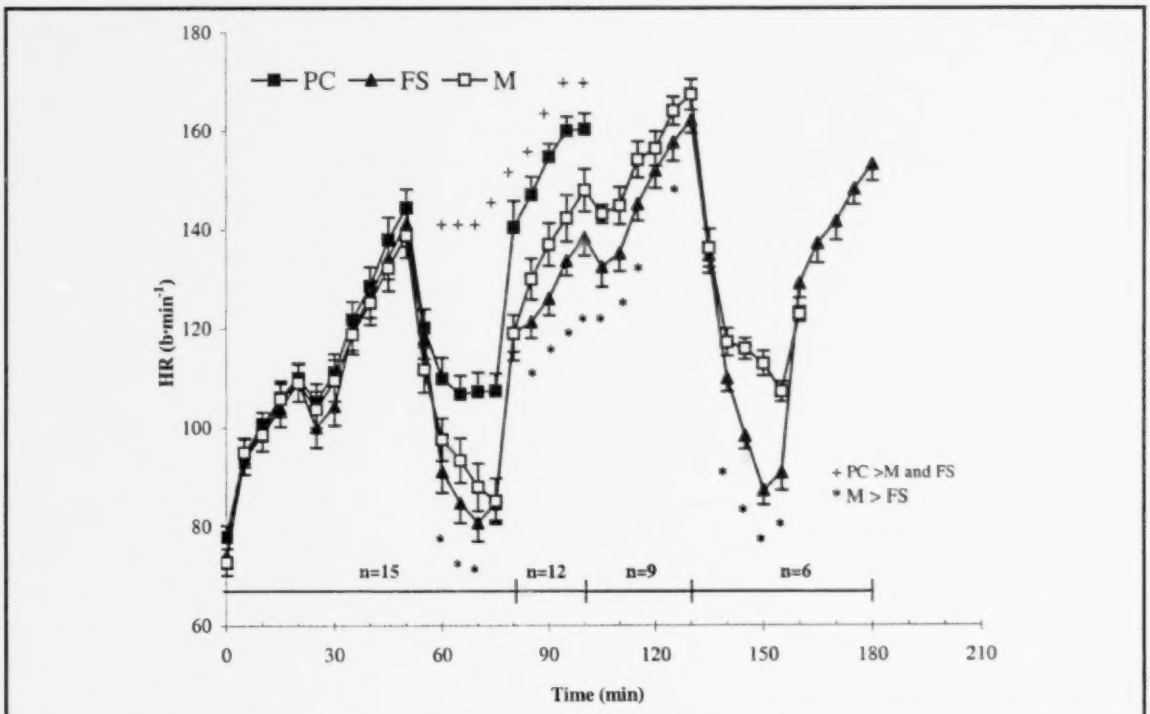

FIGURE 2. Heart rate (HR) response during passive cooling (PC), mister (M), and forearm submersion (FS) heat-stress trials at 35 C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).

TABLE I. Initial, Final, Delta (Final–Initial) Rectal Temperature (T_{re}), and the Rate of Rectal Temperature Increase During the Heat-Stress Trials at 35°C and 50% Relative Humidity

	FS	M	PC
$T_{re\ initial}$ (°C)	36.71 (0.06)	36.81 (0.07)	36.83 (0.06)
$T_{re\ final}$ (°C)	38.95 (0.10)	39.16 (0.13)	39.16 (0.07)
ΔT_{re} (°C)	2.23 (0.11)	2.35 (0.15)	2.33 (0.09)
Overall rate of T_{re} increase (°C·h^{-1})	0.79 (0.06)^{A}	1.01 (0.06)^{B}	1.30 (0.05)

Notes: Subjects were wearing full firefighting protective clothing and self-contained breathing apparatus for forearm submersion (FS), mister (M), and passive cooling (PC) conditions. Values are means (±SE) for n = 15.

^{A}F < M and PC.

^{B}M < PC.

observed during the first 50 min of work (W1) since all trials followed the same initial protocol. During the first 20-min rest period (R1), HR was significantly higher for PC compared with M and FS, and remained higher for the duration of the trial. In addition, HR for FS was significantly lower compared with M during R1, as well as during the second work (W2) and rest (R2) periods. There were no significant differences observed during transition periods between FS and M.

Rectal Temperature

The values for initial rectal temperature ($T_{re\ initial}$), final rectal temperature ($T_{re\ final}$), and delta rectal temperature ($\Delta T_{re} = T_{re\ final} - T_{re\ initial}$) are given in Table I. There were no significant differences among the trials for these dependent measures. Although there were no significant differences among the trials for the rate of T_{re} increase during individual work periods, the overall rate of T_{re} increase throughout the heat-stress was significantly different among the trials due to the cooling method applied (Table I).

T_{re} Response Over Time

To normalize slight variations in $T_{re\ initial}$, data are shown as ΔT_{re} in Figure 3. No significant differences were observed during W1. At 60 min, ΔT_{re} for PC was significantly greater compared with FS and M. Also, M was signficantly greater than FS after min 70 of the heat-stress trials.

During R1, significant differences were observed in ΔT_{re} among all three cooling strategies and significant differences also were observed during R2, between FS and M. During R1, ΔT_{re} for PC continued to increase 0.21 ± 0.03°C at a

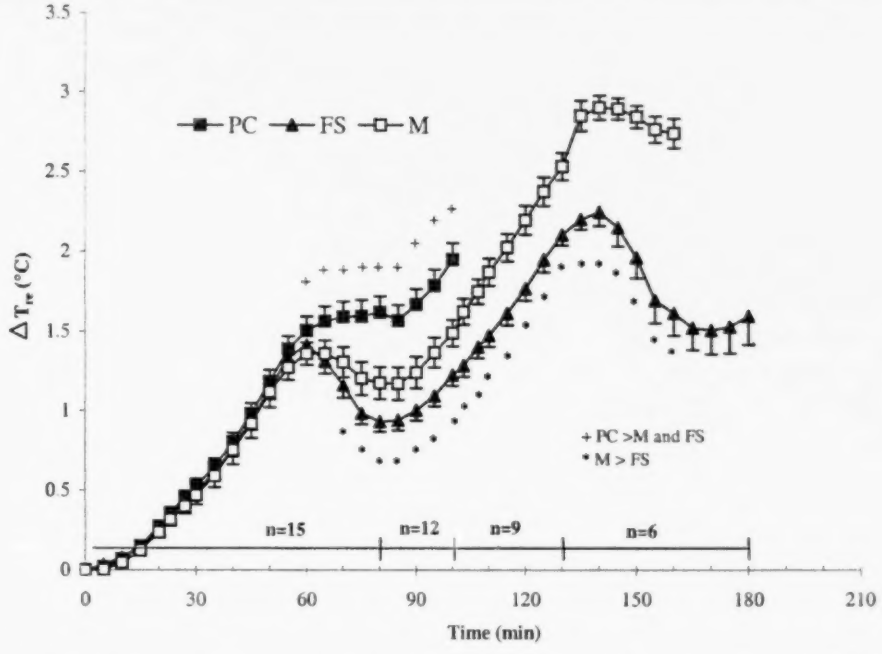

FIGURE 3. Delta rectal temperature (ΔT_{re}) response during passive cooling (PC), mister (M), and forearm submersion (FS) heat-stress trials at 35°C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).

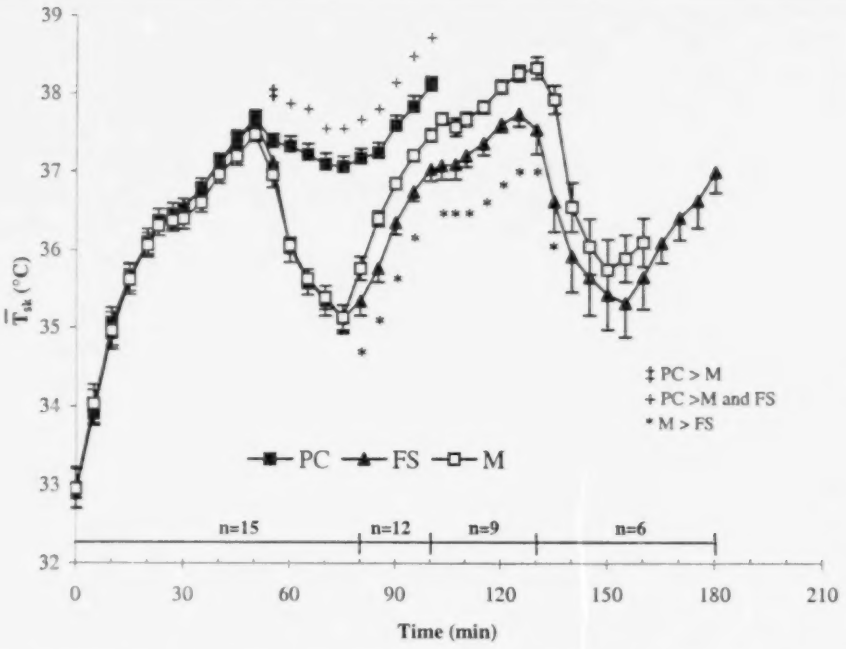

FIGURE 4. Mean skin temperature ($\bar{T}_{sk}$) response during passive cooling (PC), mister (M), and forearm submersion (FS) heat-stress trials at 35 C and 50% relative humidity, with subjects wearing full firefighting protective clothing and self-contained breathing apparatus. Values are means (±SE).

rate of 0.62 ± 0.1°C·h^{-1}, whereas ΔT_{re} during R1 for M and FS decreased by 0.07 ± 0.05 and 0.35 ± 0.2 C at rates of 0.21 ± 0.2 and 1.05 ± 0.16°C·h^{-1}, respectively. Similarly, ΔT_{re} during R2 decreased 0.09 ± 0.1 and 0.50 ± 0.1°C at rates of 0.26 ± 0.3 and 1.50 ± 0.4°C·h^{-1} for M and FS, respectively. There were no significant differences observed between R1 and R2 for either M or FS.

Mean Skin Temperature

The $\bar{T}_{sk}$ response for the cooling trials is depicted in Figure 4. After 55 min, $\bar{T}_{sk}$ was significantly greater for PC when compared with M, and after 60 min when compared with FS. In addition, M was significantly greater than FS from the beginning of E2 from 80 to 135 min. There were no other significant differences observed. Although, $\bar{T}_{sk}$ was not significantly different during the first 80 min when comparing FS and M, there were significant differences observed in hand temperature during submersion. Hand skin temperatures dropped to 20°C during the FS trial compared with only 32°C during the M trial.

Mean Body Temperature and Heat Storage

Mean body temperature ($\bar{T}_b$) decreased 0.90 ± 0.05°C and 0.65 ± 0.04°C during R1 for FS and M, respectively. In comparison, there was no significant difference observed in $\bar{T}_b$ for PC during R1. During R2, $\bar{T}_b$ decreased 0.95 ± 0.10 and 0.73 ± 0.10 for FS and M, respectively. Heat storage (ΔS) decreased 270.5 ± 17.8 kJ and 195.0 ± 13.4 kJ during R1 and 277.1 ± 42.9 and 207.5 ± 35.0 kJ during R2 for FS and M, respectively. Comparatively, during R1, ΔS for PC increased 9.17 ± 11.6 kJ. All comparisons for $\bar{T}_b$ and ΔS were significantly different during R1 among the cooling trials.

Tolerance Time

There were significant differences in TT and WT observed across all three trials (Table II). Comparing PC to M and FS showed significant increases in TT by 30 and 66%, respectively. Similarly, WT increased for M and FS by 25 and 62%, respectively, in comparsion to PC. Forearm submersion also significantly increased TT and WT approximately 30% compared with M, an increase equivalent to 30 min or approximately one bottle of air. Reasons for trial termination of the sessions are illustrated in Table II for the various cooling trials. Of the 45 experimental sessions, 47% (21 of 45) were terminated with subjects complaining of exhaustion, 10 of which occurred during the FS trial. A further 29% (13 of 45) were terminated because T_{re} reached 39.5°C during the trial and HR and dizziness/nausea accounted for the remaining 24%.

TABLE II. Tolerance Time (TT), Total Work Time (WT), and Reasons for Termination of the Heat-Stress Trials Conducted at 35°C and 50% Relative Humidity

	FS	M	PC
TT (min)	178.7 (13.00)[A]	139.1 (8.28)[B]	108.0 (3.59)
WT (min)	124.7 (7.94)[A]	95.1 (4.96)[B]	78.0 (3.59)
Reasons for Trial Termination			
T_{re}	2	7	4
Exh	10	3	8
HR	3	2	2
Dizziness/nausea	0	3	1
Time (290 min)	0	0	0

Notes: Subjects were wearing full firefighter protective ensemble and self-contained breathing apparatus for forearm submersion (FS), mister (M), and passive cooling (PC) conditions. Values represent the number of subjects during each trial that attained a rectal temperature (T_{re}) of 39.5°C, ended due to exhaustion (Exh), reached or exceeded a heart rate (HR) of 95% HR_{peak} for 3 min, ended due to dizziness or nausea, or attained the time limit of 290 min of work. Values are means (±SE) for n = 15.

[A]F > M and PC.

[B]M > PC.

TABLE III. Sweat Rate (SR), Total Fluid Intake, Total and Percent Body Mass Change, and the Percentage of Water Given That was Consumed During the Heat Stress Trials at 35°C and 50% Relative Humidity

	FS	M	PC
SR ($kg \cdot h^{-1}$)[A]	0.81 (0.08)	0.93 (0.08)	1.26 (0.07)
Total fluid intake (kg)[A]	2.31 (0.19)	1.94 (0.14)	1.72 (0.12)
Total mass lost (kg)	0.35 (0.17)	0.39 (0.10)	0.62 (0.09)
Body mass loss (%)	0.40 (0.19)	0.45 (0.12)	0.73 (0.11)
Water consumption %	86.2 (4.66)	83.8 (4.20)	86.7 (5.45)

Notes: Subjects were wearing full firefighting protective clothing and self-contained breathing apparatus for forearm submersion (FS), mister (M), and passive cooling (PC) conditions. Values are means (±SE) for n = 15.

[A]All comparisons significantly different.

Environmental Conditions and Water Bath Temperatures

Ambient environmental conditions remained constant for PC and FS at 35°C and 50% RH (2.81 kPa) throughout the trials. Mister cooling decreased the local ambient temperature by 4.3 ± 0.6°C and increased humidity by 23.4 ± 3.6% producing an ambient condition of 31.7°C and 73.4% RH (3.24 kPa) during rest phases. Water bath temperatures during FS trials increased 2.7°C during R1 and 3.3°C during R2. Heat transferred to the water during the 20 min submersion was 312.1 ± 13.0 W, and 392.5 ± 12.4 W for R1 and R2, respectively. There was a significantly greater heat transfer during min 0–10 (216.9 ± 10.3 W and 259 ± 15.6 W) compared with min 10–20 (95.2 W ± 5.3 W and 132.7 ± 8.9 W) for R1 and R2, respectively. As well, R2 was significantly greater than R1.

Sweat Rate, Body Mass Loss, and Fluid Replacement

Sweat rate, mass loss, and fluid replacement values are given in Table III for PC, M, and FS. There were significant differences in SR and total fluid consumption for all comparisons within the heat-stress trials. Although a full fluid replacement schedule was attempted, there was still a decrease in body mass, but this was less than 0.8%.

Rating of Thermal Comfort

Rating of thermal comfort corresponded to the level of T_{re} observed during the heat-stress trials. RTC values were significantly elevated at 65 min during PC (8.7 ± 0.3) when compared with M (7.2 ± 0.2) and FS (6.4 ± 0.2). In addition, FS was significantly lower compared with M at 65 min and remained throughout R2. Despite the decreased RTC values during M and FS, there were no significant differences observed at trial termination among the three cooling strategies (mean = 10.7 ± 0.3) due to differences in TT.

DISCUSSION

The purpose of the present study was to compare the effectiveness of forearm submersion, mister, and passive cooling strategies during intermittent rest periods and to determine whether one modality was more effective than another in aiding heat transfer from the body while wearing FPC and SCBA. Although we could not simulate the radiant heat of direct fire exposure in our climatic chambers, we recognized that many firefighting activities do not involve direct exposure to a fire but still entail wearing FPC and SCBA, such as during overhaul, salvage, and response to emergency calls that encorporate the risk of exposure to unknown agents. An environmental condition of 35°C and 50% RH was chosen to represent a very warm summer's day for the temperate climate region of Toronto.

In the present study, forearm submersion clearly was effective in reducing the heat strain associated with a given workload as well as extending total work time, although a thermal equilibruim was not attained. These results demonstrate the detrimental effects a cummulative oscillating heat storage can have during repeated bouts of work. The addition of active cooling allowed the reduction of the heat strain at a given time but was not able to prevent the eventual exhaustion of participating subjects.

Hand and forearm submersion in cool water produces a vasoconstriction of the arteriovenous anastomoses (AVA) through centrally mediated temperature receptors in order to maintain thermal equilibrium. However, when the body is in a hyperthermic state, it has been shown that vasodilation of AVAs is not compromised at water temperatures ranging from

10–30°C.[20,22,23] Optimal water bath temperatures have been found to be between 10–20°C, with the cooler water producing faster rates of body cooling at the onset, with a subsequent plateau observed after 20–30 min of submersion.[20] Since the increase in water bath temperature in the present study remained relatively constant, it is unlikely that the observed change in skin temperature was due to peripheral vasoconstriction.

Furthermore, the fact that T_{re} reductions were seen during the first 10 min of submersion not only supports the notion of peripheral vasodilation but also the notion that cooled blood from the hands and forearm flows directly to the core via superficial veins as opposed to deep veins.[22] Countercurrent heat exchange between arteries and deep veins would warm the cooled blood returning to the core thereby slowing the rate of body cooling in response to the hand and forearm submersion.

Mean transfer of heat to the water bath was comparable to previous work using extremity submersion at 20°C.[20,21] As well, a greater heat transfer to the water bath was observed during the first 10 min of the submersion compared with min 10–20, as has been previously reported.[20,21] This observation can be attributed to an elevated heat transfer gradient at the beginning of the submersion. As T_{re} approached normal values, peripheral perfusion decreased due to vasoconstrictive responses of the AVAs. At the same time, the temperature of the water bath increased, decreasing the heat transfer gradient and subsequent heat transfer. In contrast, submersion in cold water during a normothermic state (37.0°C) would produce only a minimal change in T_{re} due to the mediated vasoconstrictive response to maintain thermal equilibrium.[26]

Effectiveness of the mister depends on the ability to exchange the humidity of the microenvironment with the ambient envirionment. In the current study the mister affected heat transfer in several ways. First, the increased effective air velocity with the fan promoted greater evaporative and convective heat transfer. Second, the flash evaporation of the fine water mist led to a reduction in local temperature from 35 to 30°C, which also promoted a greater convective heat transfer. However, the mister led to an increase in RH by 20% and an increase in local environmental vapor pressure from 2.8 to 3.1 kPa, thus reducing the evaporative potential of the environment.[1,28]

It has been suggested that oscillating changes in T_{re} may have an affect on fatigue.[19] Although $T_{re\,final}$ was not significantly different among the cooling trials, there did appear to be a tendency for individuals during the FS trial to have a lower T_{re} at exhaustion, suggesting that subjects ended their trial due to factors other than reaching our ethical T_{re} constraint. This idea is further illustrated by the subjects' reasons for trial termination, with a greater number of subjects ending due to HR and exhaustion during the FS trial compared with M (see Table II).

Furthermore, although M was able to extend tolerance and work times by approximately one bottle of air compared with PC, elevated rates of heat storage caused a greater number of subjects to reach critical rectal temperature levels and/or dizziness and nausea compared with FS. Comparing the M and FS trials at the end of W2, T_{re} was 0.43°C higher in M compared with FS, and by the end of R2, the difference in T_{re} was even greater, 39.4°C versus 38.5°C. Thus, although M helps to increase TT, there is a limited reduction of thermal strain, as was depicted by elevated $\bar{T}_{sk}$, T_{re}, and HR values compared with FS over time.

Potentially, the mister rest period could be extended to further reduce T_{re} to levels seen during FS. However, this would decrease work time and hinder productivity. Incorporating more than one mister in a large space could increase the cooling effects. However, in a closed space, using more than one mister would be self-defeating due to additional increases in ambient vapor pressure. It is possible that in a closed space the use of fans alone may be just as effective. Another possibility would be to use ice water in the mister container to increase cooling power.

One way to increase the effectiveness of the submersion would be to use a combination of hands and feet,[20] although this may not always be a practical method in the field. To produce similar benefits to that of combined hand and foot submersion, the amount of time that the hands alone are submerged could be increased, keeping in mind that limb submersion is considered to be a self-limiting method.[20] Once the body reaches a normothermic state, peripheral vasoconstriction will prevent any further body heat loss during submersion. Thus, extending the length of a rest period may not achieve a substantial benefit for body cooling. In fact, it has been found that cooling power at 10°C and 20°C plateaues after 25–30 min as gradients decrease and rectal temperatures approach normal values.[20] Indeed, 10°C appears to be an optimal temperature for heat loss;[21] however, to increase the applicability of the present findings, a temperature (~18°C) was chosen that would be indicative of the subjects' field environment. Hypothetically, the cooler water could be achieved by adding a block of ice to the water bath, causing a greater heat transfer gradient and thus resulting in a greater cooling of personnel, assuming that AVA perfusion was maintained.

In the past, the implementation of work and rest cycles have helped to increase total work time, assuming that environmental conditions allow for cooling during rest periods.[12] At higher ambient conditions or when wearing protective clothing while remaining encapsulated, work and rest schedules may not allow for more total work to be accomplished. Furthermore, even removing restrictive clothing during rest, such as SCBA and upper body protective gear, may not be adequate to extend total work times at higher ambient conditions or metabolic rates. For example, in our previous work, firefighters following a continuous work protocol similar to the present study produced tolerance times of 67 min with a rate of T_{re} increase of 1.75°C·h^{-1} at 35°C and 50% RH. Given that the T_{re} cut-off was a conservative 39.0°C, and that seven of nine subjects reached T_{re} cut-offs, subjects' TT would have increased by 0.29 hour or 17 min if they had been allowed to continue until T_{re} values equalled 39.5°C. This would have created tolerance times of 84 min while performing continuous work at similar work rates and ambient environmental conditions.

In contrast, in the present study, working intermittently with passive cooling (removing upper body protective gear) produced an average TT of 108 min of which 78 min represented actual work time. In this theoretical comparison, TT was extended with passive rest, but the amount of total work performed was reduced (78 versus 84 min). However, by incorporating an active cooling stategy during the designated rest periods, WT was increased by 25 and 60% during M and FS, respectively, when compared with PC.

When dealing with protective clothing ensembles in an occupational health and safety setting, the goal is to set limits such that individuals never reach their critical limits. From this view point, it is preferred that a firefighter succumbs and stops work due to physical exhaustion as opposed to heat exhaustion, similar to what has been observed during work at higher metabolic work rates.[13,14,42] Not only did forearm submersion extend TT and WTs by 60%, compared with passive cooling and 30% compared with the mister trials, there was a significant reduction in the thermal strain associated with the given workload at a specific period of time. The implications of this finding is that even if the cooling is not used to extend total work time, it will significantly reduce the heat strain associated with any given task. Ultimately, this would help to reduce the occurrence of heat-related injury and possibly myocardial infarction in active firefighters.

CONCLUSIONS

In extreme environmental conditions, active cooling may be the only viable option for reducing the heat strain associated with wearing FPC and SCBA for extended periods of time. The current findings suggest that active cooling has the ability to reduce both the cardiovascular and thermoregulatory strain, while significantly increasing TT and WT where operationally necessary. In addition, there is a definite advantage during work in FPC and SCBA when utilizing forearm submersion compared with other methods of active or passive cooling in the heat.

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